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(54) **EMS TUNABLE TRANSISTOR**

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(51) **Int. Cl.**
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(52) **U.S. Cl.** **257/213**; 257/252; 257/254; 257/417; 257/415

(58) **Field of Classification Search** 257/324, 257/347, E29.309, E27.112, 213, 254, 252, 257/417, 415
See application file for complete search history.

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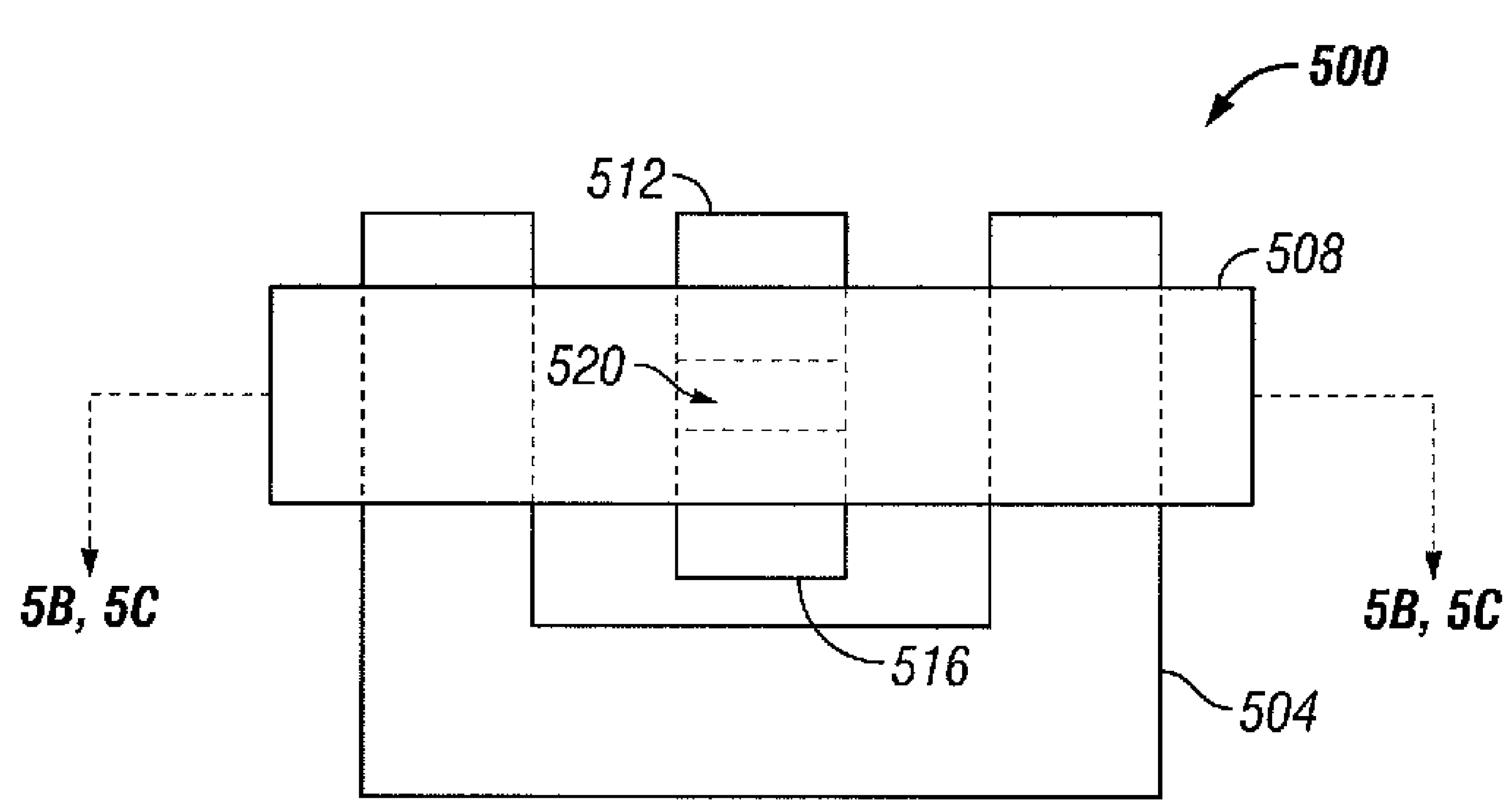
(57) **ABSTRACT**

A field effect transistor comprises an electrostatically moveable gate electrode. The moveable gate is supported by at least two posts, and the source, drain, and channel of the transistor are centrally located under the moveable layer. At least one electrode is positioned on at least two sides of the source, drain, and channel.

27 Claims, 4 Drawing Sheets



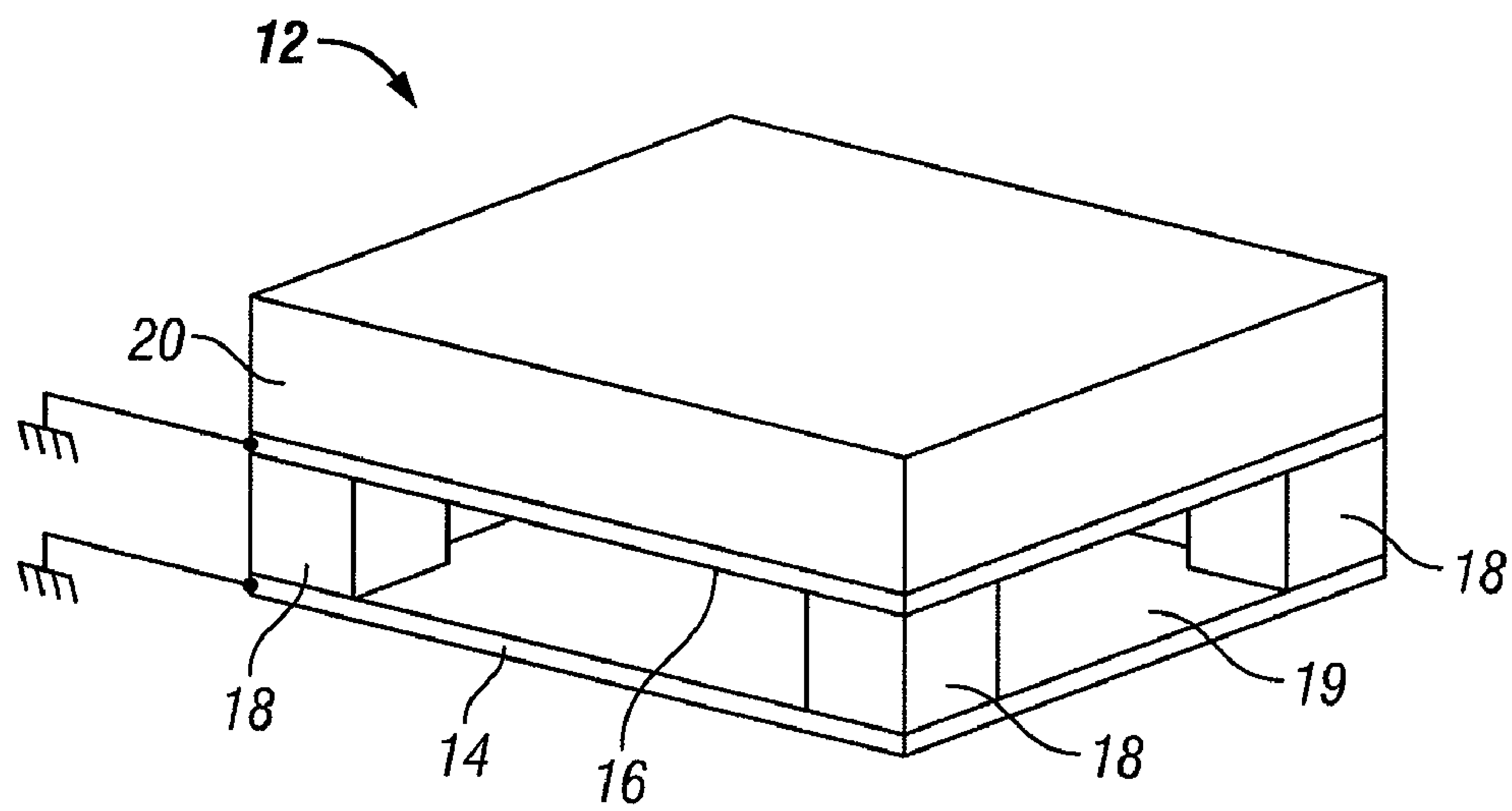


FIG. 1

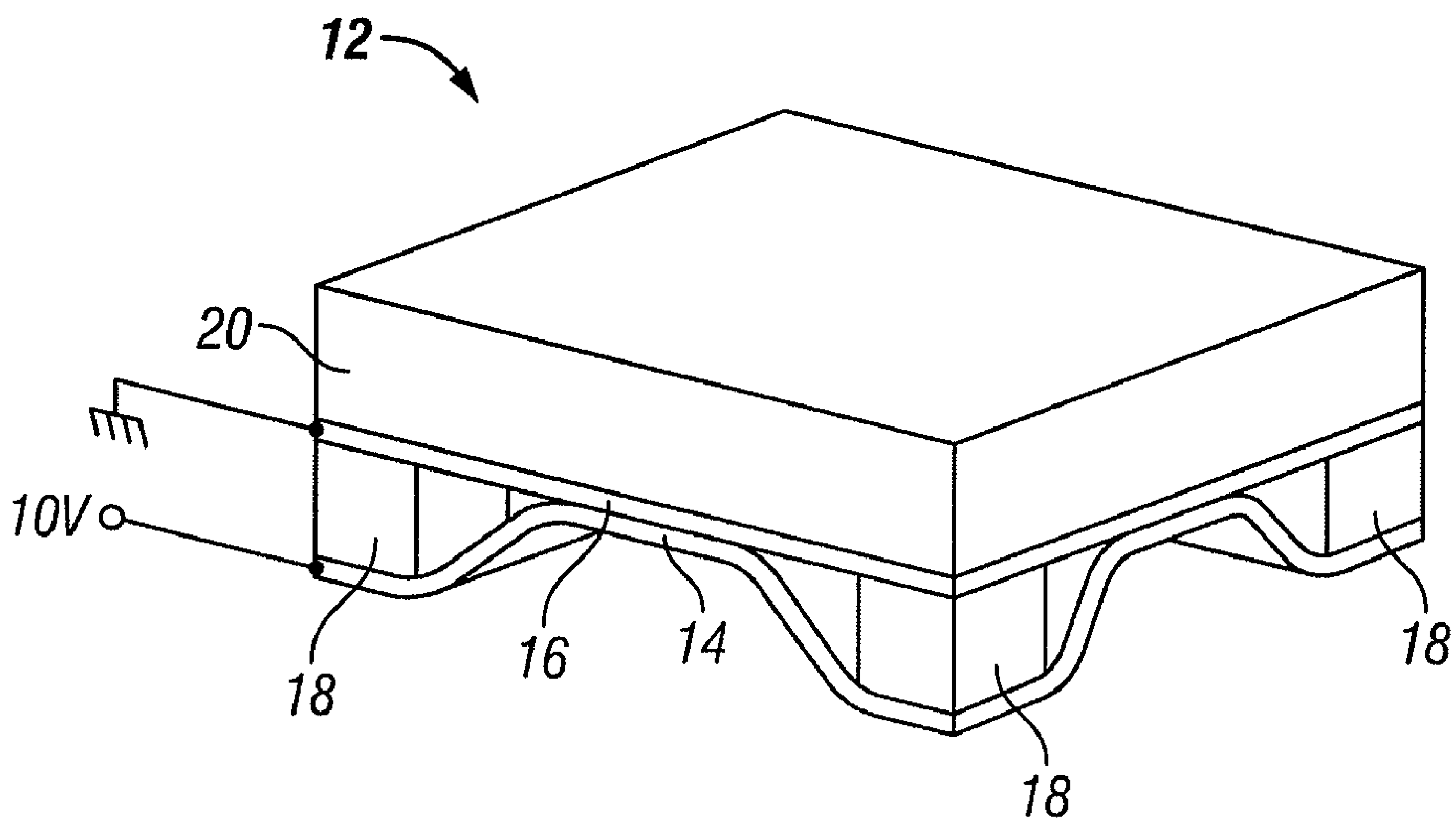


FIG. 2

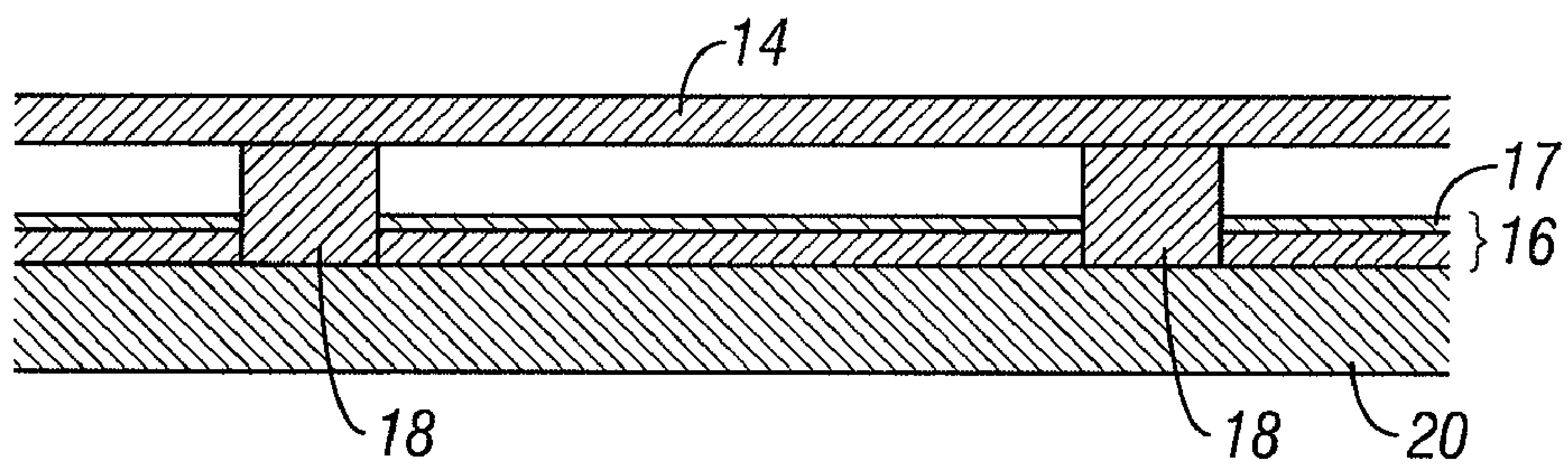


FIG. 3A

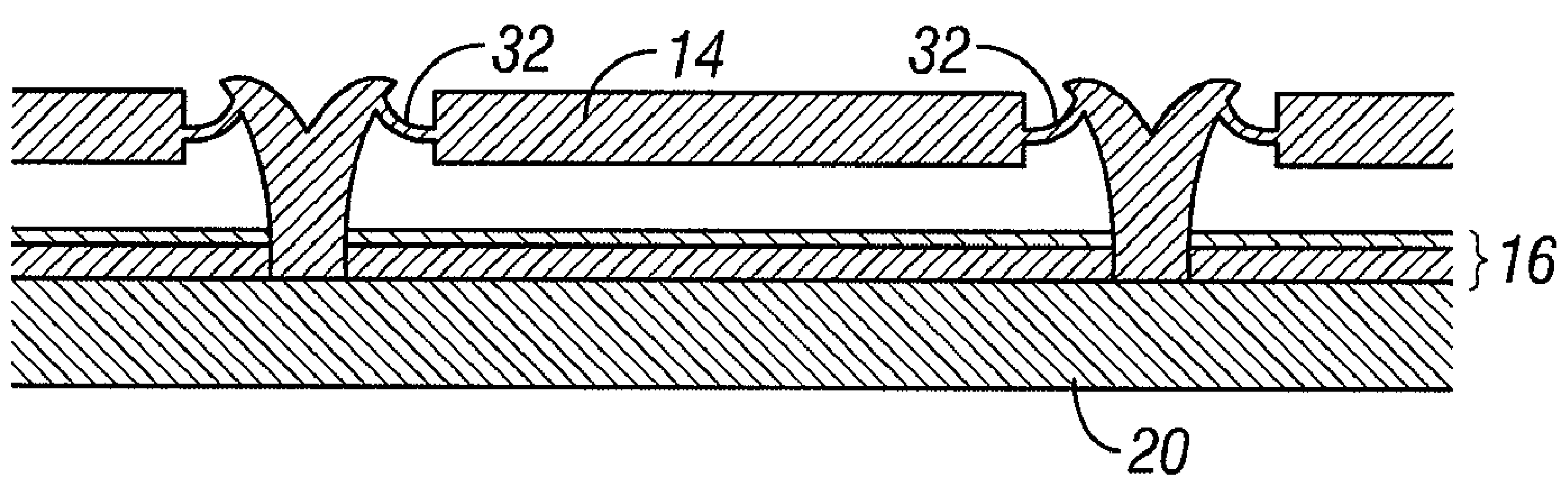


FIG. 3B

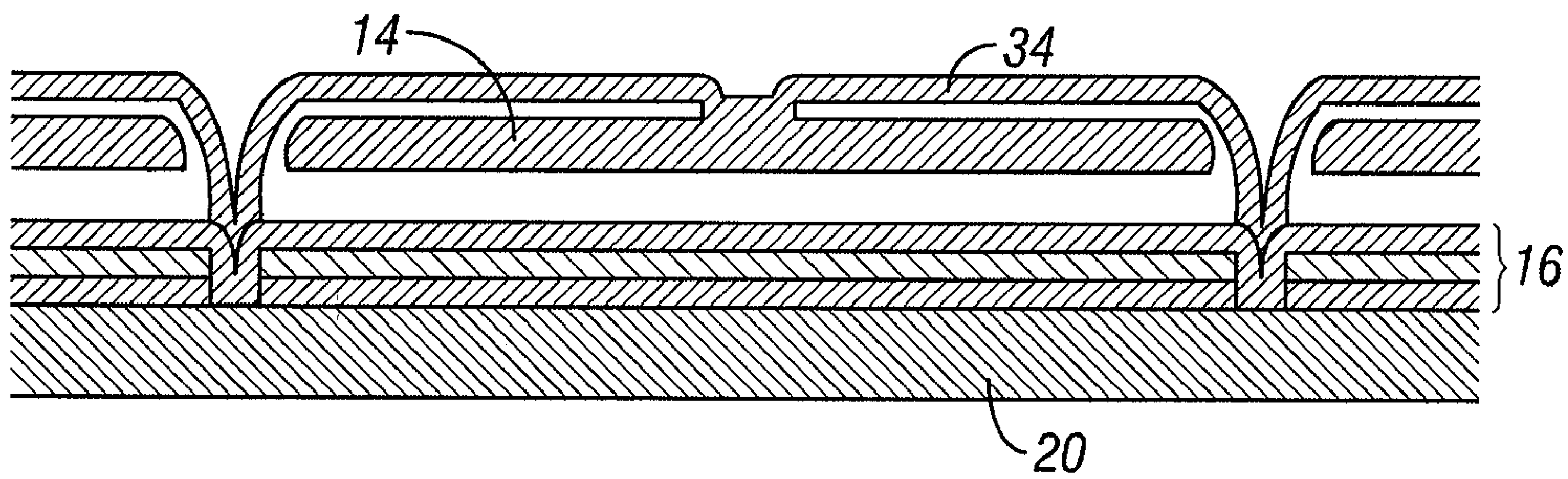


FIG. 3C

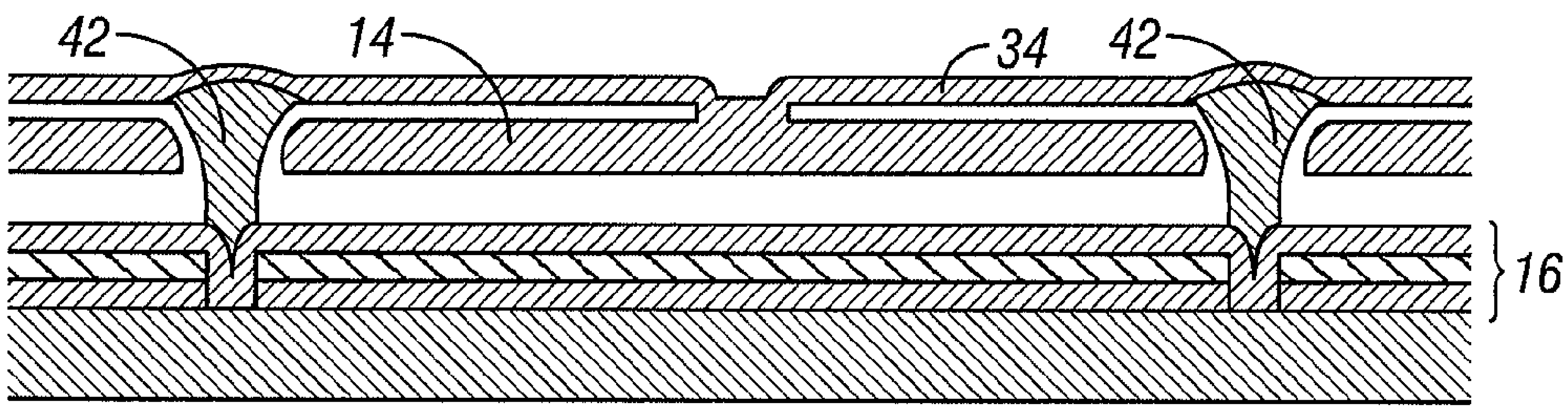


FIG. 3D

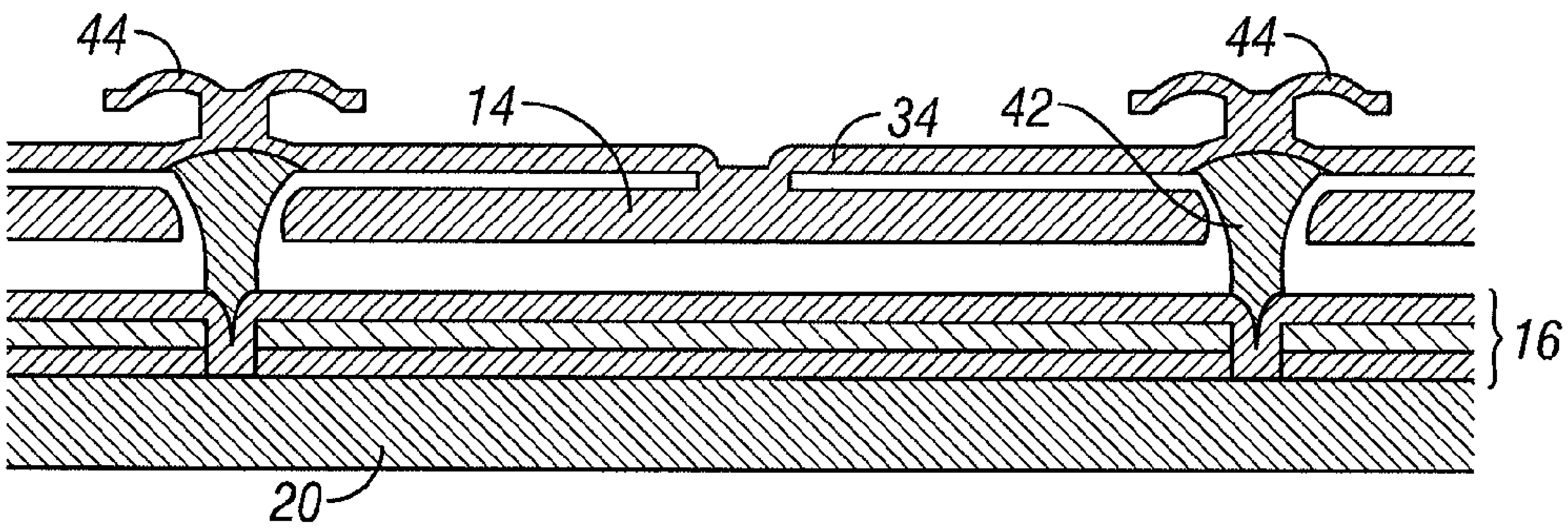


FIG. 3E

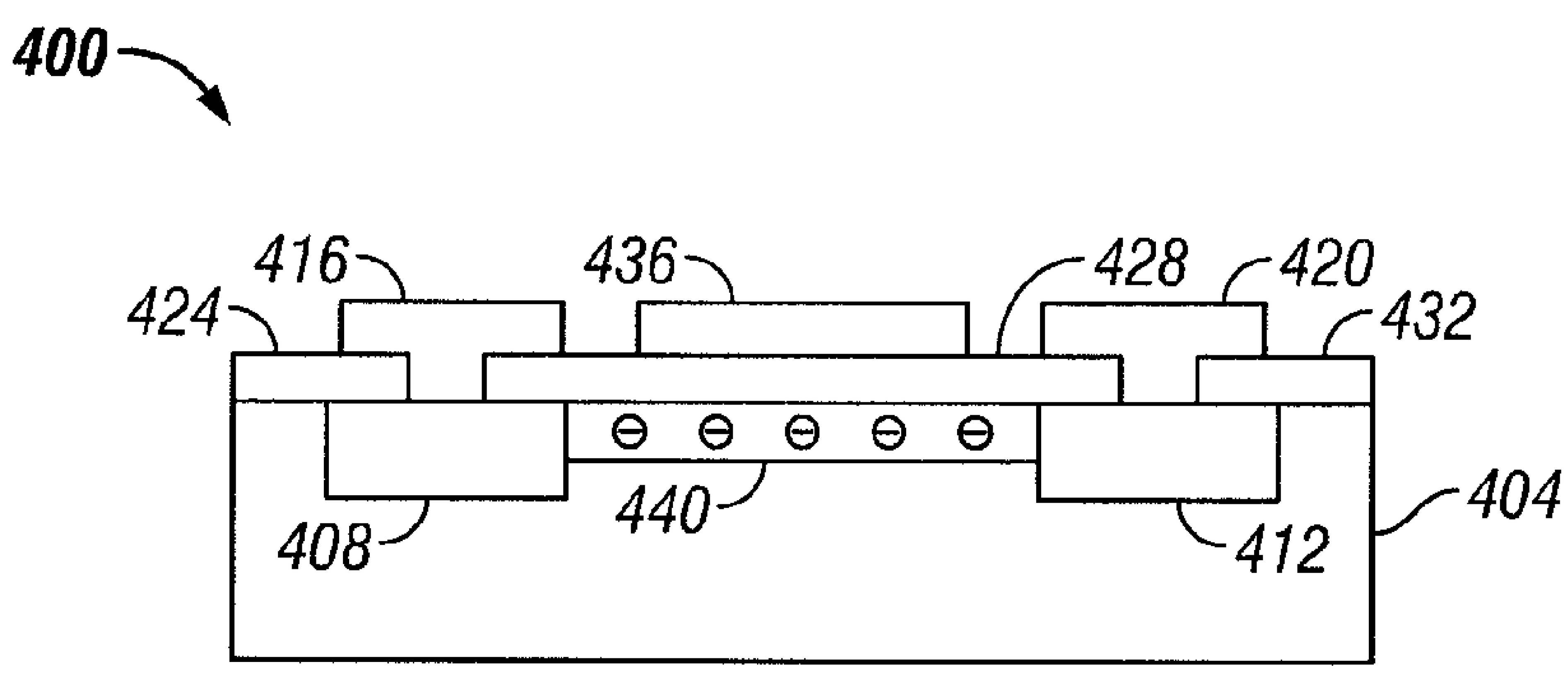


FIG. 4

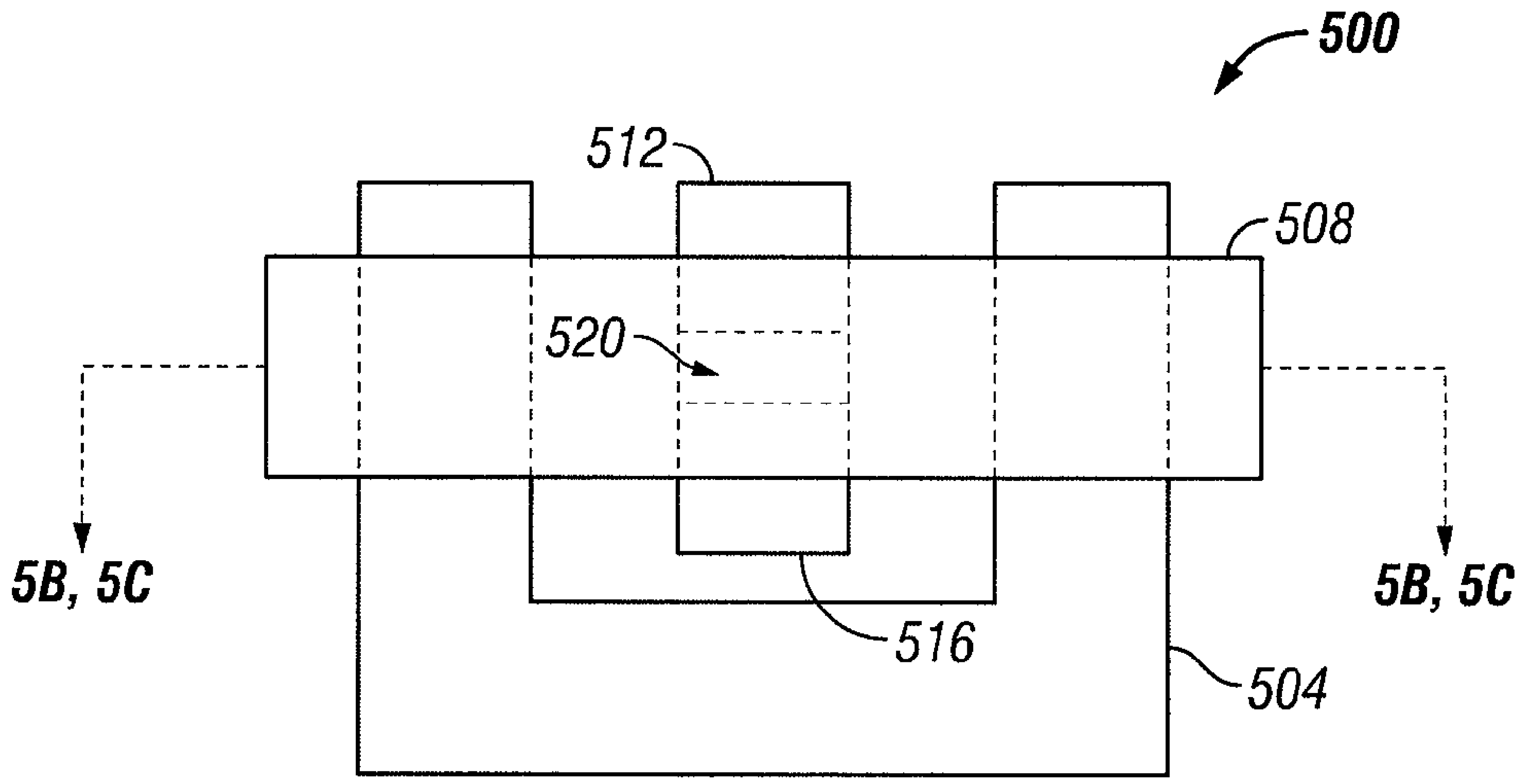


FIG. 5A

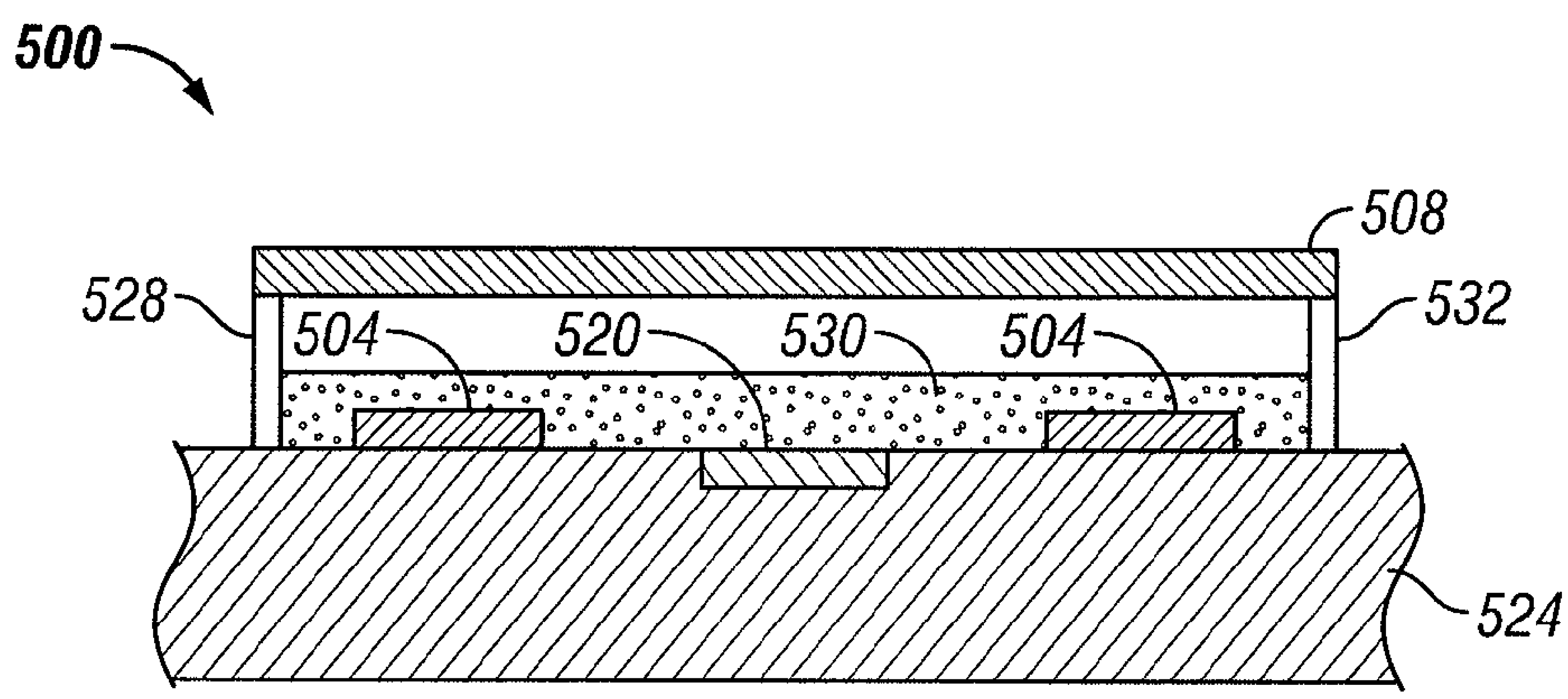


FIG. 5B

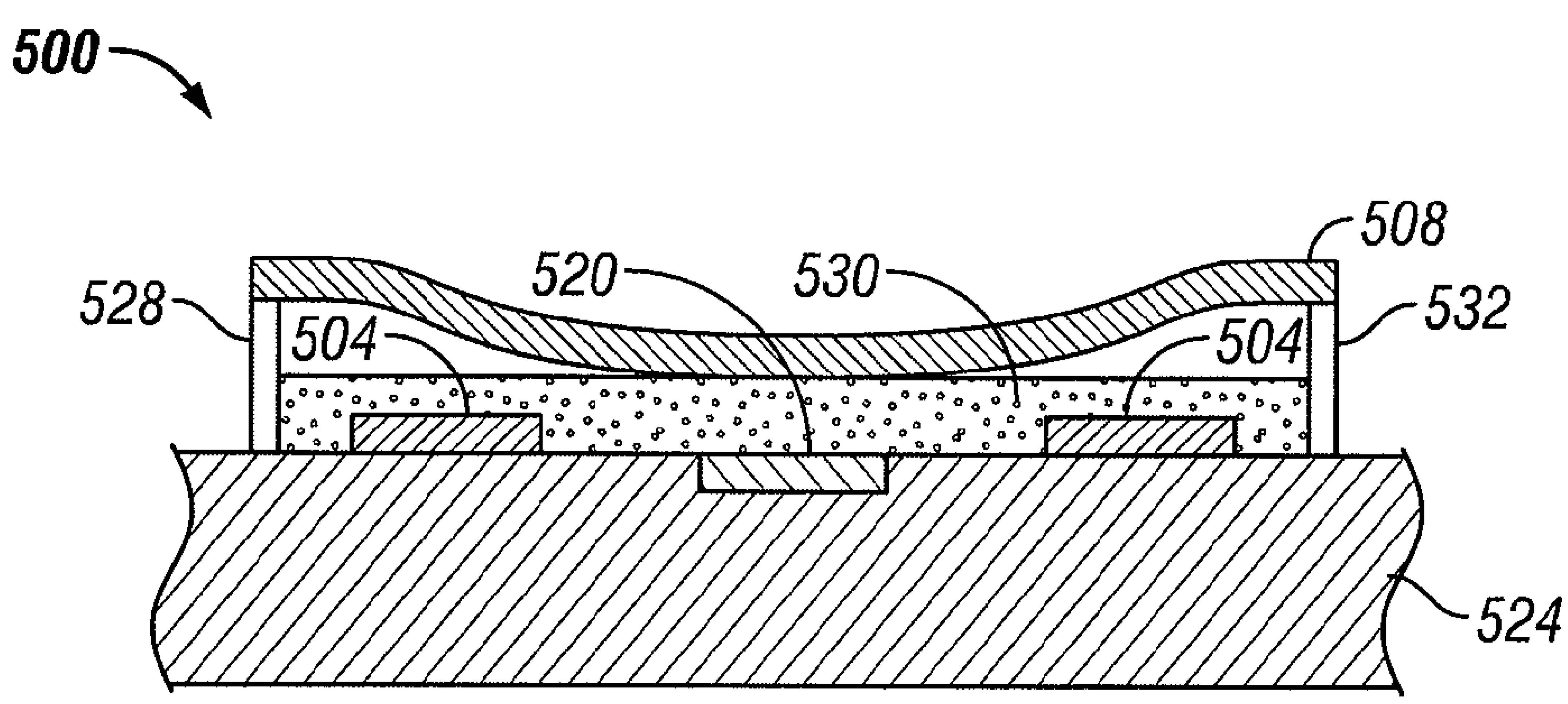


FIG. 5C

EMS TUNABLE TRANSISTOR

TECHNICAL FIELD

This disclosure relates to electromechanical systems (EMS). More particularly, this disclosure relates to EMS devices used as transistors.

DESCRIPTION OF THE RELATED TECHNOLOGY

Electromechanical systems (EMS) include, for example, milli, micro, nano mechanical elements, actuators, and electronics. Electromechanical elements may be created using deposition, etching, and or other machining processes that etch away parts of substrates and/or deposited material layers or that add layers to form electrical and electromechanical devices. One type of EMS device is called a capacitive EMS device. As used herein, the term capacitive EMS device refers to a device which includes at least one layer which moves towards another layer. In certain implementations, a capacitive EMS device may include a pair of conductive plates, one or both of which may be transparent and/or reflective in whole or part and capable of relative motion upon application of an appropriate electrical signal. In a particular implementation, one plate may include a stationary layer deposited on a substrate and the other plate may include a metallic membrane separated from the stationary layer by an air gap. Such devices have a wide range of applications, and it would be beneficial in the art to utilize and/or modify the characteristics of these types of devices so that their features can be exploited in improving existing products and creating new products that have not yet been developed.

SUMMARY

In one implementation, the disclosure includes a field effect transistor including a moveable gate supported by at least two posts and configured to deform centrally between the at least two posts, a source, a drain, and a doped semi-conductor channel disposed between the source and the drain and located under the movable gate. The transistor further includes one or more electrodes disposed on at least two sides of the source, the drain and the doped semi-conductor channel and configured to drive the moveable gate towards or away from the doped semi-conductor channel.

In another implementation, a method of operating a field effect transistor includes electrostatically moving a gate of the transistor toward a source, a drain and a doped semi-conductor channel of the transistor, wherein the gate is supported by at least two posts and is configured to deform centrally towards the source, the drain, and the doped semi-conductor channel, and wherein one or more electrodes are disposed on at least two sides of the source, the drain and the dope semi-conductor channel.

In another implementation, a field effect transistor includes a moveable gate supported by at least two posts and configured to deform centrally between the at least two posts, a source, a drain, a doped semi-conductor channel disposed between the source and the drain and located under the movable gate; and means for moving the gate towards or away from the doped semi-conductor channel, wherein the moving means is disposed on at least two sides of the source, the drain and the doped semi-conductor channel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an isometric view of a capacitive EMS device in which a movable layer is in a relaxed position.

FIG. **2** is an isometric view of a capacitive EMS device in which a movable layer is in an actuated position.

FIG. **3**A is a cross section of the device of FIG. **1**.

FIG. **3**B is a cross section of one implementation of a capacitive EMS device.

FIG. **3**C is a cross section of one implementation of a capacitive EMS device.

FIG. **3**D is a cross section of one implementation of a capacitive EMS device.

FIG. **3**E is a cross section of one implementation of a capacitive EMS device.

FIG. **4** is a diagram of an exemplary transistor including a capacitive EMS device.

FIG. **5**A is a top view of an exemplary transistor.

FIG. **5**B is a vertical cross section of the exemplary transistor of FIG. **5**A in a relaxed state.

FIG. **5**C is a vertical cross section of the exemplary transistor of FIG. **5**A in an actuated state.

DETAILED DESCRIPTION

FIGS. **1** and **2** are isometric views depicting a first implementation and a second implementation of a capacitive EMS device in which a movable layer of the capacitive EMS device as shown in FIG. **1** is in a relaxed position and a movable layer of the capacitive EMS device as shown in FIG. **2** is in an actuated position. In these implementations, the capacitive EMS devices are in either a "relaxed" or "actuated" state. In the "relaxed" (e.g., "open") state, the movable layer is positioned at a relatively large distance from a fixed layer. When in the "actuated" (e.g., "closed") state, the movable layer is positioned more closely adjacent to the fixed layer.

FIG. **1** is an isometric view depicting a portion of one implementation of a capacitive EMS device **12** in which a movable layer of a capacitive EMS device **12** is in a relaxed position. In some implementations, a consumer good or an electronic device, for example, may include a row/column array of these capacitive EMS devices. Each capacitive EMS device includes a pair of layers (e.g., a fixed layer and a movable layer) positioned at a variable and controllable distance from each other to form a resonant gap with at least one variable dimension. In one implementation, one of the layers (e.g., the movable layer) may be moved between two positions. In the first position shown in FIG. **1**, referred to herein as the relaxed position, the movable layer is positioned at a relatively large distance from a fixed layer. In the second position shown in FIG. **2**, referred to herein as the actuated position, the movable layer is positioned more closely adjacent to a fixed layer.

In the capacitive EMS device **12** shown in FIG. **1**, a movable layer **14** is illustrated in a relaxed position at a predetermined distance from a conductive stack **16**. In the capacitive EMS device **12** shown in FIG. **2**, the movable layer **14** is illustrated in an actuated position adjacent to a stack **16**.

The stack **16**, as referenced herein, may include several fused layers, which can include a conductive electrode layer, such as aluminum or indium tin oxide (ITO), and a dielectric. The stack **16** is thus electrically conductive, may be partially transparent and partially reflective, and may be fabricated, for example, by depositing one or more of the above layers onto a substrate **20**. In some implementations, the layers of the stack **16** may form one or more electrodes in an electronic device. The movable layer **14** may be one or more deposited metal layers formed on posts **18** and on top of an intervening sacrificial material (not shown) deposited between the posts **18**. When the sacrificial material is etched away, the movable layer **14** is separated from the stack **16** by a defined gap **19**. A highly conductive material such as aluminum may be used for the movable layer **14**, and these may form one or more electrodes in an electronic device. Note that FIG. **1** may not be to scale. In some implementations, the spacing between posts **18** may be on the order of 10-100 um, while the gap **19** may be on the order of <1000 Angstroms.

With no applied voltage, the gap **19** remains between the movable layer **14** and stack **16**, with the movable layer **14** in a mechanically relaxed state, as illustrated by the capacitive EMS device **12** in FIG. **1**. However, when a potential (voltage) difference is applied between the stack **16** and the movable layer **14**, the capacitive EMS device becomes charged in a manner similar to charging a capacitor, and electrostatic force acts on the stack **16** and movable layer **14**. If the voltage is high enough, resulting in a correspondingly high electrostatic force, the movable layer **14** is deformed and is forced against the stack **16**, as shown in FIG. **2**. A dielectric layer (such as dielectric layer **17** shown in FIG. **3**A) on top of the stack **16** (or on the movable layer **14**) may prevent shorting and control the separation distance between layers **14** and **16**, as illustrated by actuated capacitive EMS device **12** of FIG. **2**. The behavior is the same regardless of the polarity of the applied potential difference. If the voltage is subsequently removed between the stack **16** and the movable layer **14**, the movable layer **14** returns to a mechanically relaxed state as shown in FIG. **1**. The moveable layer **14**, acting like a spring, returns to the mechanically relaxed state due to a mechanical restorative force (i.e., a spring force) exerted by the moveable layer **14** due to its deflection.

In some implementations, the stack **16** can serve as a common electrode that provides a common voltage to one side of the capacitive EMS device of an electronic device. The movable layers may be formed as an array of separate plates arranged in, for example, a matrix form. The separate plates can be supplied with voltage signals for driving the capacitive EMS devices.

The details of the structure of capacitive EMS devices that operate in accordance with the principles set forth above may vary widely. For example, FIGS. **3**A-**3**E illustrate five different implementations of the movable layer **14** and its supporting structures. FIG. **3**A is a cross section of the implementation of FIG. **1**, where a strip of metal material **14** is deposited on orthogonally extending supports **18**. In FIG. **3**B, the moveable layer **14** of each capacitive EMS device is square or rectangular in shape and attached to supports at the corners only, on tethers **32**. In FIG. **3**C, the moveable layer **14** may be square or rectangular in shape and suspended from a deformable layer **34**, which may include a flexible metal. The deformable layer **34** connects, directly or indirectly, to the substrate **20** around the perimeter of the deformable layer **34**. These connections are herein referred to as support posts. The implementation illustrated in FIG. **3**D has support post plugs **42** upon which the deformable layer **34** rests. The movable layer **14** remains suspended over the gap, as in FIGS. **3**A-**3**C, but the deformable layer **34** does not form the support posts by filling holes between the deformable layer **34** and the stack **16**, or fixed layer. Rather, the support posts are formed of a planarization material, which is used to form support post plugs **42**. The implementation illustrated in FIG. **3**E is based on the implementation shown in FIG. **3**D, but may also be adapted to work with any of the implementations illustrated in FIGS. **3**A-**3**C as well as additional implementations not shown. In the implementation shown in FIG. **3**E, an extra layer of metal or other conductive material has been used to form a bus structure **44**. This allows signal routing along the back of the capacitive EMS devices, eliminating a number of electrodes that may otherwise have had to be formed on the substrate **20** or elsewhere.

Capacitive EMS devices (such as the ones illustrated in FIGS. **1** and **2**) may be used in a variety of electronic devices. For example, capacitive EMS devices are used in displays, where the movement/deformation of the movable layer may be used to vary at least one of the wavelength, color, and frequency of light waves which may be reflected by the capacitive EMS device.

Capacitive EMS devices may also be used as transistors or may be used as parts of transistors. In the implementations described herein, the moveable layer of a capacitive EMS device is used as a gate electrode of a field effect transistor.

FIG. **4** is a diagram of an exemplary field effect transistor **400**. The transistor **400** may include a metal-oxide-semiconductor field-effect transistor (MOSFET). The transistor **400** may be used for a variety of functions including but not limited to amplifying and/or switching electronic signals. In one implementation, the transistor **400** may be an N-type transistor including a P-substrate **404** (e.g., a positive type substrate). The transistor **400** also includes two N-type (e.g., negative type) regions **408** and **412**, which are located within the P-substrate **404**. The N-type region **408** is coupled to a source terminal **416**. The source terminal **416** may be coupled to a voltage source (not shown in figure). The N-type region **412** may be coupled to a drain terminal **420**. The transistor **400** also includes insulating regions **424**, **428**, and **432** which are positioned above the P-substrate **404** and the N-type regions **408** and **412**. A gate **436** is positioned above the insulating region **428** and between source terminal **416** and drain terminal **420**. The gate **436** may be coupled to a voltage source (not shown in this figure). A conductive channel **440** is positioned between the N-type regions **408** and **412**. The conductivity of the transistor **400** is dependent, at least in part, on the voltage applied to the gate **436** and the distance between the gate **436** and the channel **440**.

Although FIG. **4** is directed towards an N-type transistor, the implementations described herein may be applicable to P-type transistors. A P-type transistor is similar to the N-type transistor shown in FIG. **4**. However, in a P-type transistor, regions **408** and **412** would be P-type (e.g., positive type) regions and the substrate **404** would be an N-substrate (e.g., a negative type substrate).

FIG. **5**A is a top view of a second exemplary transistor **500** in a capacitive EMS device. The transistor **500** may be, for example, a metal-oxide-semiconductor field-effect transistor (MOSFET). The transistor **500** may be used for a variety of functions including but not limited to amplifying and/or switching electronic signals. The transistor **500** includes an electrode **504**. A gate (e.g., a movable layer) **508** is positioned above the electrode **504**. The transistor also includes two N-type (e.g., negative type) regions **512** and **516**, which are located within the P-substrate **524** shown in FIG. **5**B. In one implementation, the N-type region **512** may be coupled to a drain terminal (not shown in figure) and the N-type region **516** may be coupled to a source terminal (not shown in figure). The electrode **504** may be coupled to a voltage source (not shown in figure). The source terminal (not shown in figure) may also be coupled to a voltage source (not shown in figure). The N-type regions **512** and **516** may be located within a P-substrate **524** (shown in FIGS. **5**B through **5**C). The transistor channel **520** is positioned between the N-Type regions **512** and **516**. The region under the moveable layer **508** may include a dielectric **530** (shown in FIGS. **5**B through **5**C).

As shown in this Figure, the source **516**, drain **512**, and channel **520** of the transistor are centrally located under the moveable layer **508**, and the electrode **504** is placed on at least two sides of these transistor elements. This arrangement assures that the moveable layer **508** is sensitive to potential differences between the electrode **504** and moveable gate **508**, and that the use of the electrode **504** to position the gate does not unduly affect the operation of the transistor.

Although the electrode **504** is shown as a single "U" shaped segment, other implementations may use a variety of shapes or a different number of electrodes. The electrode may totally surround regions **512** and **516**. As another example, there may be two rectangular shaped electrodes, one on either side of the N-type regions **512** and **516**. In another implementation, two square shaped electrodes may be placed on either side of the N-type regions **512** and **516**. In a further implementation, more than two electrodes may be placed around the N-type regions **512** and **516**. For example, three or four electrodes may be positioned on the sides and above and below the N-type regions **512** and **516**.

In addition, different implementations may orient the placement of the gate **508** and/or the electrode **504** in different ways. For example, in one implementation, the gate **504** may be positioned to extend vertically across the transistor **500**, rather then horizontally across the transistor as shown in FIG. **5**A. In another implementation, the electrode **504** may also be positioned such that it forms a "C" shape rather than a "U" shape as shown in FIG. **5**A.

FIG. **5**B is a vertical cross section of the second exemplary transistor **500** of FIG. **5**A in a relaxed state. The gate **508** is positioned above the electrode **504**, the conductive channel **520**, and the N-Type regions **512** and **516** (shown in FIG. **5**A). The gate is held in place via posts **528** and **532**. The N-type regions **512** and **516** are positioned within a P-substrate **524**. The electrode **504** is positioned above the P-substrate **524**, the N-type regions **512** and **516**, and the conductive channel **520**. The electrode **504** is also positioned below the gate **508**.

In other implementations, the electrode **504**, the N-type regions **512** and **516**, and the conductive channel **520** may be placed in different locations. For example, in one implementation, the electrode **504**, the N-type regions **512** and **516**, and the conductive channel **520** may all be positioned within the P-substrate **524**. In another implementation, the electrode **504**, the N-type regions **512** and **516**, and the conductive channel **520** may all be positioned above the P-substrate **524**. In yet another implementation, the electrode **504**, and the N-type regions **512**, **516**, may be positioned above the P-substrate **524**, but the conductive channel **520** may be positioned within the P-substrate **524**.

In FIG. **5**B, the transistor **500** may be in an "off" state or an "inactive" state or a "relaxed" state. In this state, less electric current may flow through the conductive channel **520** between N-type regions **512** and **516** (e.g., an electric current cannot flow between N-type regions **512** and **516**). It may be noted that while the gate is farther from the channel in this relaxed state, there may still be electric current flowing between the regions **512** and **516** through the channel when voltages are appropriately applied on the gate, source and drain terminals. The current depends on the capacitance between the gate and the channel, and in the relaxed state, there is still some capacitance between them.

FIG. **5**C is a vertical cross section of the second exemplary transistor **500** of FIG. **5**A in an actuated state. In FIG. **5**C, a voltage differential is present between the gate **508** and the electrode **504**. The voltage differential between the gate **508** and the electrode **504** may be present due to a voltage applied at one or both of the gate **508** and the electrode **504**. For example, in one implementation, a voltage may be applied at the gate **508** and ground voltage may be applied at the electrode **504**. In another implementation, a voltage may be applied at the electrode **504** and ground voltage may be applied at the gate **508**. In yet another implementation, a first voltage may be applied at the electrode **504** and a second voltage (which may be higher or lower then the first voltage) is applied at the gate **508**. When the voltage differential is present between the gate **508** and the electrode **504**, electrostatic forces may cause the gate **508** (e.g., a movable layer) to deform and/or move towards the electrode **504**. If the voltage differential between the gate **508** and the electrode **504** is subsequently removed, the gate **508** (e.g., a movable layer) returns to a mechanically relaxed state as shown in FIG. **5**B. The gate **508**, acting like a spring, returns to the mechanically relaxed state due to a mechanical restorative force (i.e., a spring force) exerted by the gate **508** due to its deflection. In one implementation, the gate **508** may be movable into two positions (e.g., the relaxed position shown in FIG. **5**B and the actuated position shown in FIG. **5**C). In another implementation, the gate **508** may be movable into any position between the relaxed position shown in FIG. **5**B and the actuated position shown in FIG. **5**C. For example, the gate **508** may only be partial deformed and/or moved towards the electrode **504**. The closer the gate **508** is moved (e.g., deformed or deflected) towards the electrode **504**, the closer the gate **508** is positioned to the conductive channel **520**, and more electric current may flow through the conductive channel **520**. In FIG. **5**C, the transistor **500** may be in an "on" state or an "active" state or an "actuated" state. In this state, electric current may flow through the conductive channel **520** between N-type regions **512** and **516**, as similarly described in FIG. **4**B.

Although FIGS. **5**A through **5**C are directed towards an N-type transistor, the implementations described herein may be applicable to P-type transistors. A P-type transistor is similar to the N-type transistor shown in FIGS. **5**A through **5**C. However, in a P-type transistor, regions **512** and **516** would be P-type (e.g., positive type) regions and the substrate **524** would be an N-substrate (e.g., a negative type substrate).

The transistor **500** shown in FIGS. **5**A through **5**C has multiple transistor characteristics. Examples of transistor characteristics include but are not limited to drain current, transconductance, cut-off frequency, breakdown voltage, leakage current, and the capacitance between at least two of the source, gate, and drain of the transistor **500**. Any of these parameters may be affected by the position of the moveable layer **508**.

In one implementation, the transistor of FIGS. **5**A-**5**C is utilized in a feedback circuit. The feedback circuit may control the amount of voltage applied at the electrode **504** and/or the gate **508**. The feedback circuit may modify the amount of voltage applied at the electrode **504** and/or the gate **508** based at least in part on one or more transistor characteristics. For example, the feedback circuit (not shown in figure) may increase and/or decrease the voltage applied at the electrode **504** and/or the gate **508** based on the drain current. In another implementation, the feedback circuit may increase and/or decrease the voltage applied at the electrode **504** and/or the gate **508** based on the drain current and the leakage current.

In one implementation, the increase and/or decrease in the voltage applied at the electrode **504** and/or the gate **508** may increase and/or decrease the distance between the gate **508** and the conductive channel **520**. After fabrication of the transistor **500**, the initial distance between the gate **508** and the electrode **504** may be changed based on at least one transistor characteristic. For example, following fabrication of the transistor **500**, the distance between the gate **508** and the electrode **504** may be decreased based on the leakage current measured for the transistor **500**. After the initial distance between the gate **508** and the conductive channel **520** has been changed to a final distance, the final distance may be substantially fixed.

While the above detailed description has shown, described and pointed out novel features of the disclosure as applied to various implementations, it will be understood that various omissions, substitutions, and changes in the form and details of the modulator or process illustrated may be made by those skilled in the art without departing from the spirit of the disclosure. As will be recognized, the present disclosure may be embodied within a form that does not provide all of the features and benefits set forth herein, as some features may be used or practiced separately from others.

What is claimed is:

1. A field effect transistor comprising:
- a moveable gate supported by at least two posts and configured to deform centrally between the at least two posts;
- a source;
- a drain;
- a doped semi-conductor channel disposed between the source and the drain and located under the movable gate; and
- one or more electrodes disposed on at least two sides of the source, the drain and the doped semi-conductor channel and configured to drive the moveable gate towards the doped semi-conductor channel.

2. The transistor of claim **1**, wherein the one or more electrodes drive the movable gate towards the doped semi-conductor channel when a voltage difference is present between the one or more electrodes and the moveable gate.

3. The transistor of claim **1**, the doped semi-conductor channel conducts an electric current when the movable gate is driven towards the doped semi-conductor channel.

4. The transistor of claim **1**, wherein at least one transistor characteristic is based at least in part on a distance between the moveable gate and the doped semi-conductor channel.

5. The transistor of claim **1**, wherein the at least one transistor characteristic comprises at least one of a drain current, transconductance, a cut-off frequency, a breakdown voltage, a leakage current, and a capacitance between at least two of the source, gate and drain of the field effect transistor.

6. The transistor of claim **4**, wherein the drain current increases as the distance between the moveable gate and the doped semi-conductor channel decreases.

7. The transistor of claim **1**, wherein the one or more electrodes is further configured to drive the movable gate towards the one or more electrodes.

8. The transistor of claim **1**, wherein the one or more electrodes is further configured to drive the moveable gate towards at least one of the source and the drain.

9. The transistor of claim **1**, wherein the moveable gate is driven towards the doped semi-conductor channel due to an electrostatic force.

10. The transistor of claim **1**, wherein the moveable gate is positioned above the drain, the source, and the doped semi-conductor channel and wherein the one or more electrodes is positioned below the moveable gate.

11. The transistor of claim **1**, wherein a distance between the movable gate and the doped semi-conductor channel is changed and substantially fixed after the fabrication of the transistor, and wherein the change is based at least in part on at least one transistor characteristic.

12. The transistor of claim **1**, wherein the distance between the movable gate and the doped semi-conductor channel is varied based at least in part on an electrical signal.

13. The transistor of claim **12**, wherein the electrical signal is based on, at least in part, an electrical feedback circuit.

14. The transistor of claim **1**, wherein a spring force of the moveable gate drives the moveable gate away from the doped semi-conductor channel.

15. A method of operating a field effect transistor, the method comprising electrostatically moving a gate of said transistor toward a source, a drain and a doped semi-conductor channel of said transistor, wherein the gate is supported by at least two posts and is configured to deform centrally towards the source, the drain, and the doped semiconductor channel, and wherein one or more electrodes are disposed on at least two sides of the source, the drain and the dope semi-conductor channel.

16. The method of claim **15**, wherein the gate is moved towards or away from the doped semi-conductor channel due to the voltage difference between the one or more electrodes and the gate.

17. The method of claim **15**, the doped semi-conductor channel conducts an electric current when the movable gate is driven towards the doped semi-conductor channel.

18. The method of claim **15**, wherein at least one of a drain current, transconductance, and a cut-off frequency of the field effect transistor is based at least in part on a distance between the moveable gate and the doped semi-conductor channel.

19. The method of claim **18**, comprising increasing the drain current as the distance between the gate and the doped semi-conductor channel decreases.

20. The method of claim **15**, comprising moving the gate towards the one or more electrodes.

21. The method of claim **15**, further comprising moving the gate towards at least one of a source and a drain.

22. The method of claim **15**, further comprising moving the gate away from the source, the drain, and the doped semiconductor channel based on a spring force of the gate.

23. A field effect transistor comprising:
- a moveable gate supported by at least two posts and configured to deform centrally between the at least two posts;
- a source;
- a drain;
- a doped semi-conductor channel disposed between the source and the drain and located under the movable gate; and
- means for moving the gate towards or away from the doped semi-conductor channel, wherein the moving means is disposed on at least two sides of the source, the drain and the doped semi-conductor channel.

24. The transistor of claim **23**, wherein the moving means comprises one or more electrodes.

25. The transistor of claim **23**, wherein the moving means uses an electrostatic force to move the gate towards the doped semi-conductor channel.

26. The transistor of claim **23**, wherein the doped semi-conductor channel conducts an electric current when the movable gate is moved towards the doped semi-conductor channel.

27. The transistor of claim **21**, wherein a spring force of the moveable gate drives the moveable gate away from the doped semi-conductor channel.

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